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On the Need for Multidimensional Stirling Simulations

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Abstract

Given the cost and complication of simulating Stirling convertors, do we really need multidimensional modeling when one-dimensional capabilities exist? This paper provides a comprehensive description of when and why multidimensional simulation is needed.

I. Introduction

Power conversion with free-piston Stirling engines[1,2] has the potential to deliver high efficiency, low mass solutions for longer and more varied space missions.[3,4] The design of free-piston Stirling engines has largely been accomplished utilizing one-dimensional Navier-Stokes solvers. One of the objectives of computer analysis is to determine an approximate optimum design prior to building any hardware. A one-dimensional analysis design code does not provide all of the geometrical details, but can be used to determine overall volume and configuration information, including some of the geometrical details. The one-dimensional models can be set up quickly and the computations are fast. And perhaps most importantly, design optimizations are easily done in one-dimension.

This paper will demonstrate that one-dimensional analysis has an important place in Stirling engine design, but that the design process really needs multidimensional capability as well to:

- verify the one-dimensional results,
- properly simulate inherently three-dimensional turbulence–including transition, (includes understanding the effects of flow vortices in expansion, compression and other spaces on engine performance),
- provide empirical heat transfer and friction factor coefficients for complex geometries to aid in hardware design and to avoid requiring hardware tests to improve one-dimensional analysis assumptions,
- integrate all the parts into a CAD system and test for structural and relative motion issues in the overall design,
- assist experimentalists in determining flow and heat transfer physics in regions where measurements are difficult or impossible,
- provide a fluid-structure interaction capability,
- generate linear reduced order models for controller development

- model large, high-power Stirling applications or devices in which the one-dimensional flow assumption breaks down (even some relatively low power, low Δt, designs approach a "pancake" shape that could not be well modeled with one-dimensional codes,

- identify areas of excessive flow losses due to unintended dead zones, recirculation zones, dissipative turbulence and other losses such as: [5,6,7]

  1. Inefficient heat exchange and pressure loss in the regenerator, heater and cooler,
  2. Gas spring and working space loss due to hysterisis and turbulence,
  3. Appendix gap losses due to pumping and shuttle effects,
  4. Mixing gas losses from nonuniform temperature and flow distributions perpendicular to primary engine flow axis,
  5. Conduction losses from the hot to cold regions
  6. Losses due to combined radiation, conduction and convection in void volumes
  7. And in general, inaccurate loss representations due to use of 1-D flow design codes to account for flow and heat transfer through area changes (between components) where phenomena such as flow separation and jetting from tubes or slots into a regenerator may occur.

This paper will highlight why multidimensional Stirling analysis is useful and critical for future designs.

II. Description of the Problem

The dual opposed configuration shown in Fig. 1 [8,9,10] is being developed for multimission use (i.e., for use in atmospheres and space), including providing electric power for potential missions such as unmanned Mars rovers and deep space missions.[11]

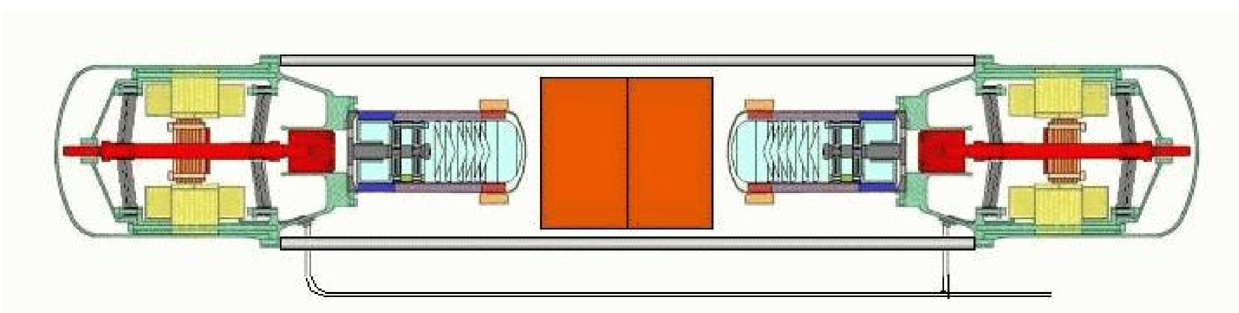


Figure 1. Dual Opposed Stirling Convertors Reduce Vibration (Schreiber)

Only the Stirling engine part of the convertor (Fig. 2) is simulated multi-dimensionally although one could anticipate the entire convertor may one day be prototyped digitally before build-up.

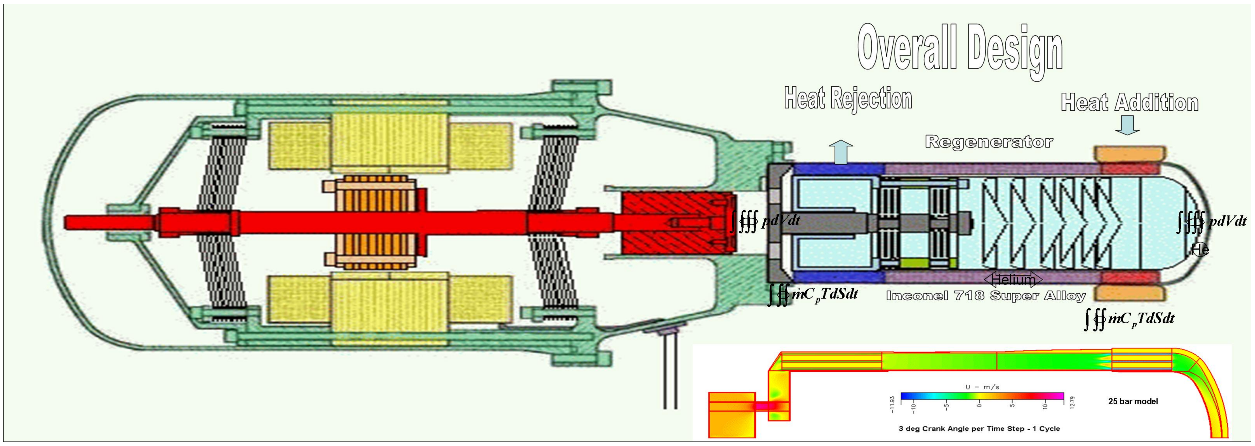


Figure 2. Stirling Engine Part of Convertor Simulated Only

An example of the desired full Stirling engine simulation is shown in Fig. 3.[12] It is anticipated that full 3D simulations will provide a level of geometric and flow detail necessary for further design improvements. For example, hardware experiments have shown that large performance gains can be made by varying manifolds and heat exchanger designs to improve flow distributions in the heat exchangers.[8,13,14]

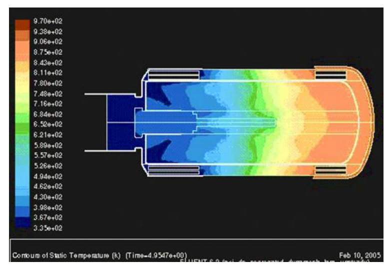


Figure 3. Example Transient Simulation of Stirling Convertor-Colored by Temperature

The kinds of flow and geometry that occur in a Stirling engine which a modeling technique must address are as follows:[7,6]

1. Oscillating flow which changes the effective conduction, flow friction coefficients and heat diffusion.[15]
2. Low mach number flow (no shocks),
3. Compressible flow due to enclosed varying volumes and heat transfer effects,
4. Laminar, Transitional, and Turbulent flow with Reynolds numbers from 100 to 10000 (based on various length scales pertinent to the flow region),
5. Conjugate heat transfer, thermal dispersion and local thermal nonequilibrium in the porous media regenerator,
6. Micron to Millimeter scale geometry[16]
7. Small separations between sliding solid-fluid interfaces in the seals and appendix gap
8. Deforming Flow Regions Due to Compression and Expansion (i.e., due to moving piston boundaries)

III. Current Stirling Cycle Analysis Approaches

The techniques of analysis for Stirling engines can be categorized with Martini's[17,18] nomenclature. We will use his definition of Third Order and discuss the recent multidimensional category.

A. Third Order Analysis

Third order analysis uses control volumes or nodes to directly solve the one-dimensional governing equations. Some of the first analysis at this level of fidelity was by Finkelstein,[19] Urieli,[20] and Berchowitz.[21]

Some other more recent third order analysis codes are:

- The codes by David Gedeon referred to as GLIMPS[22,23] and Sage[24,25,26] are one-dimensional and solve the governing equations implicitly in space and time. The grid includes all time because a periodic solution is assumed/forced. Therefore, it is not possible to model transient startup behavior.
- The linearized harmonic analysis code referred to as HFAST[27] solved a steady-state periodic problem in the frequency domain. Again, transient behavior is not modeled.
- The code by Martini engineering[28] was never validated but claimed transient modeling capability. It is not clear that rigorous governing equations are being solved since it appears many simplifications based on experimental correlations are used.
- Another unvalidated but interesting code by Renfroe[29] attempted a one-dimensional analysis using explicit Runge-Kutta time stepping and a Newton solver to solve the nonlinear equations.
- Some other recent one-dimensional solvers are LASER,[30] DeltaE,[31] ARCOPTR,[32] and REGEN3.1.[33]
- Finally, the Stirling Dynamic Model (SDM),[34] uses a one-dimensional analogy of an entire Stirling convertor by linking together representative elements within the Simplorer(TM) commercial software package by Ansoft Corp. This tool enables approximate whole convertor dynamic analysis. Recent work attempts to incorporate thermodynamics via David Gedeon's Sage code described earlier.

These approaches will continue to play an important role in Stirling analysis, even as the multidimensional analysis becomes practical to use. A full analysis package incorporating both third and fourth order analysis (defined below) will be presented in Section VI.

B. Fourth Order (Multi-Dimensional) Analysis

At this level of analysis, relatively little has been completed because the third order analysis is faster and for the most part has been an adequate engineering tool. However, to improve efficiency further (to understand and reduce losses) it will likely require a better understanding of the actual flow physics and heat transfer throughout the engine. It is impractical to measure many of these features in practical Stirling devices. Some of these features can be investigated in large scale test modules designed to simulate certain Stirling like processes (such as those being investigated at the University of Minnesota. However, CFD seems best suited for investigation of the details of the fluid and heat transfer physics in a real Stirling device. Some multi-physics analysis tools are listed below.

1. Modified Computer Aided Simulation of Turbulence (CAST)

The modified CAST code[35] is based upon the Semi-Implicit Method for Pressure-Linked Equations SIMPLE[36] method but is restricted to two dimensions.[37] It was modified to include oscillatory boundary conditions and conjugate heat transfer. It has been used to model Stirling components but has not been extended to a whole engine simulation tool.

A pressure-splitting technique was added[38] to reduce the computational requirements. It was based on separating the thermodynamic and hydrodynamic pressures so that these widely varying scales could be solved with less round-off error and better efficiency.

2. CFD-ACE

This commercial code has been used to model a two-dimensional representative Stirling engine.[39,40] It is also based upon the SIMPLE technique. The regenerator is not currently modeled correctly since thermal equilibrium is assumed between the gas and solid.

This finite volume code can utilize both structured and unstructured grids.

3. Fluent

This commercial code is also based upon the SIMPLE method (and PISO method for high speed flows). It currently has similar regenerator modeling limitations in that it is designed for non-oscillating flows. It does however have a sliding interface that could be used for appendix gap modeling on parallel computers. It is being used by several commercial manufacturers for this purpose (references are proprietary). It is also finite volume based and can utilize both structured and unstructured grids.

4. STAR-CD

The Simulation of Turbulent Flow in Arbitrary Regions (STAR)[41] code also uses SIMPLE and PISO methods. Its companion product (STAR-HPC) is the parallel computer version. It also has sliding interfaces and deforming mesh capability. It has been used in the related field of internal combustion engine piston modeling, and some Stirling engines have been modeled with it.[42]

5. CFX

This code also uses SIMPLE and PISO methods on unstructured grids. It also has sliding interfaces implemented, but no stirling engine modeling with this software has been publicly published.[43]

6. Others

While there are other in-house codes, they are usually limited to modeling only specific regions of the Stirling engine such as the regenerator, or the displacer.

IV. Recent Whole Engine Modeling

The use of two-dimensional CFD models can significantly extend the capabilities, compared to third-order analysis, for the more detailed analysis of the complex heat transfer and gas dynamical processes which occur in the internal gas circuit.[44] More recently, full 3-D calculations have been performed with a commercial code.[45] The temperature results are similar to the second order method results.[46] The multidimensionally computed power, however, was about half of the second order prediction. Moreover, along the axis of the compression space it was found the change of the temperature of the working gas was quite different from harmonic in time.

Zhang[47] claims success with modeling a 3D free-piston pseudo-Stirling engine over a 3 month run-time. More recently, a two-dimensional axisymmetric simulation of a full engine has been demonstrated and validated within the observed experimental results taken from two engines.[12] Moreover, it is possible to simulate an entire engine cycle in less than one hour by utilizing modern parallel computer architectures.

In short, the capability does now exist to perform whole engine simulations in considerably less time than previously expected.

A. Regenerator Modeling

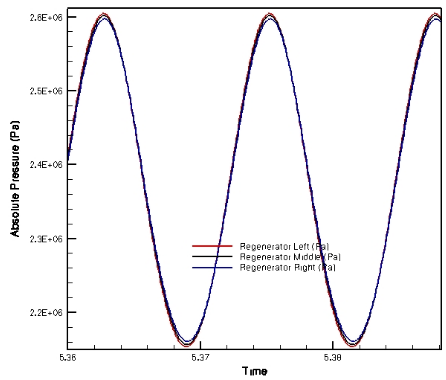


Figure 4. Importance of Properly Modeling the Regenerator for System Studies (Urieli)

A very important specific area of modeling difficulty is the regenerator. As shown in Fig. 4, since the regenerator (depending upon one's definition of effective) has roughly 3 to 40 times more effective heat transfer than the heater,[48] any inefficiency of the regenerator represents a significant loss for the entire Stirling engine. Hence, any numerical losses or inaccuracies in this region will disproportionately influence the entire Stirling simulation.

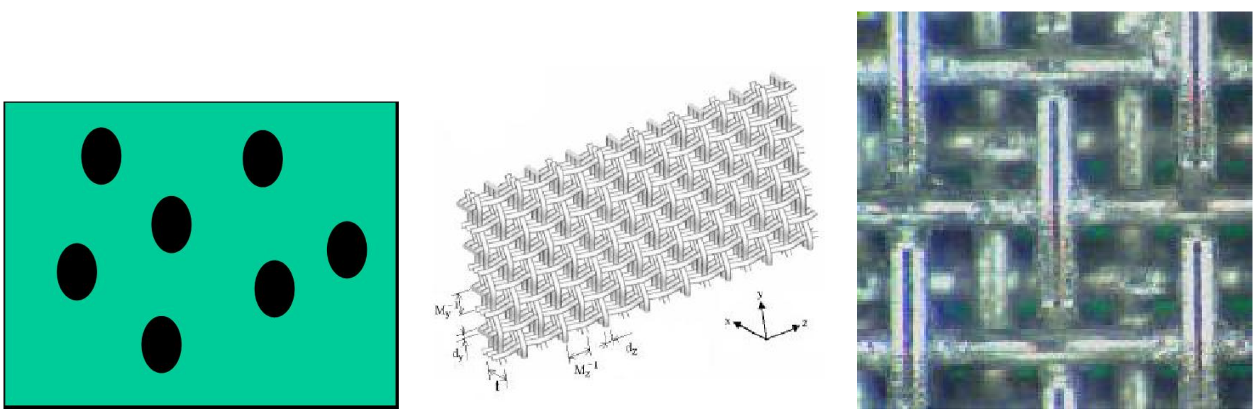
1. *Manifest*

The multidimensional code referred to as Manifest[16] solved the porous medium model equations shown below:

$$\begin{aligned}
&\frac{\partial M}{\partial \tau} + \frac{J}{\beta}\frac{\partial}{\partial y_k}\left(\frac{G^k}{J}\right) = 0 \\
&\frac{\partial G^n}{\partial \tau} + \left(J\frac{\partial}{\partial y_k}\left(\frac{G^k}{J}u_j - \frac{\beta}{J}\tau_{eij}\frac{\partial y_k}{\partial x_i}\right) + \beta J\frac{\partial}{\partial y_k}\left(\frac{P}{J}\frac{\partial y_k}{\partial x_j}\right) + \beta\psi_{jk}u_k\right)\frac{\partial y_n}{\partial x_j} = 0 \\
&\frac{\partial E}{\partial \tau} + \frac{J}{\beta}\frac{\partial}{\partial y_k}\left(\frac{E}{J}\beta u^k + \frac{1}{J}(P\beta V)^k - \frac{1}{J}(\tau_e - \beta V)^k + \frac{\beta}{J}q_e^k\right) - Q = 0 \\
&\frac{\partial}{\partial \tau}(\lambda T_s) + Q = 0
\end{aligned} \tag{1}$$

where $M = \rho, G = \beta\rho V, E = \rho e,$ using the Beam and Warming[49] implicit time stepping approach.

This code was written in curvilinear coordinates and seemed to perform well for low Reynolds number jets impinging on the matrix. It was not developed further because of excessive computational time. However, recent progress in improvements to efficiency suggest revisiting this approach.[12,50]



(a) Idealized Geomertry (b) Regularized Geometry (c) Photographed Geometry

Figure 5. Regenerator Geometry

Another important issue is the geometrical shape of the matrix in the regenerator. As shown in Fig. 5, most regenerator models don't assume a precise geometrical shape for the elements of the regenerator. However, as reported in Park,[51] a simple-to-fabricate woven mesh, consisting of bonded laminates of two-dimensional plain-weave conductive screens can be manufactured to have a wide range of porosity and a highly anisotropic thermal conductivity vector. In addition to providing superior performance in many cases,[52] the regular geometry greatly simplifies the analysis.

Clearly, the shape of the regenerator has an important impact on the overall system design and attempts have been made in the past to multidimensionally simulate the different mediums.

V. Need for Multi-Dimensional Analysis Outlined

Recent accomplishments in multi-dimensional simulation mentioned above suggest fast solutions are possible and the value of these results lie in the interplay between supporting current one-dimensional results and providing information previously unattainable. For example, the following areas are ripe for multidimensional analysis.

A. Turbulence Modeling

Since turbulence is random and inherently three-dimensional, a quasi-steady harmonic solution is capable of fully modeling its effect on pressure drop and heat transfer. A full three-dimensional Large Eddy Simulation (LES) simulation would be capable and could be utilized to determine some of the heat transfer coefficients and friction factors prior to any hardware experiments. Modeling transition effects on these coefficients appears possible by using recently developed numerical techniques.[50] This information could then be utilized by the one-dimensional solver to simulate engine components that have not been built before.

B. Verify One-Dimensional Results

The less expensive one-dimensional results are fairly accurate in most cases, so long as the empirical coefficients used are accurate. After a preliminary design is optimized with a one-dimensional code, a check on the final design with a full three-dimensional simulation would eliminate the expense and risk of building an engine that did not perform as expected when using only one-dimensional assumptions.

C. Numerical Empirical Coefficient Determination

Similar to the advantages of proper turbulence modeling, certain empirical heat transfer and flow friction factors could be obtained with multidimensional analysis when the geometry is sufficiently deviant from one-dimensional flow physics. For example, the flat head heater design by Infinia (formerly STC) was initially modeled using a one-dimensional solver but due to the complex geometry (Fig. 6) the error was over 20% until the empirical terms were adjusted.[53] Other examples include high power applications with designs that are radially wide compared to the axial length.

D. Part Integration

A conceptual one-dimensional design still does not provide adequate information for drawing actual hardware. An important aspect of a good design is not only the engine efficiency, but also it must be light-weight, reliable, and low cost. The ability to test several orientations of the parts before building them is another advantage of fourth order modeling. For example, in Fig. 7, a preliminary CAD drawing (assembly of parts) of a piston configuration and related part integration is shown.

E. Assisting Experiments

Experimental uncertainty can be minimized by multi-dimensionally simulating the experiment. Regions inside the engine are difficult to measure due to the small area or because the sensors would interfere with the flow. For example, knowledge of the temperature range experienced by the flexures throughout a cycle is important for determining the reliability of the convertor over long periods of operation in space. A full dynamic measurement of temperature distribution throughout a Stirling device is not practical due to sensor limitations and the reasons just mentioned. However, it is a fairly simple matter with multidimensional

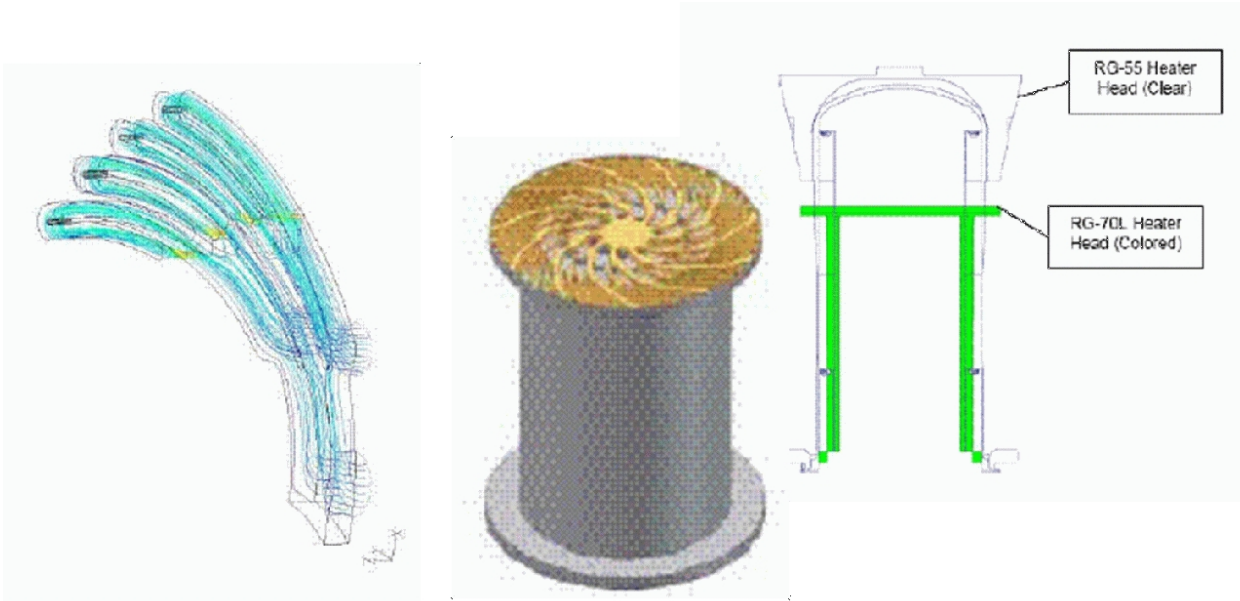


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Figure 6. Flat Head Heater Not One-Dimensional

simulations to access this data. In Fig. 8, a thermocouple cannot easily be located on the cold wall of the engine and so precise temperature information for the operating conditions of the engine are not known. However, a three-dimensional simulation has been used to identify correlations for the coldwall temperature inside a cooling jacket.

The temperature and velocity distribution throughout the engine is important for determining the kinds of materials and joining techniques. This information is also most easily determined numerically. An example of this for a simple linear alternator piston problem at one moment in time is shown in Fig. 9.

F. Fluid-Structure Interaction

The fluid forces will bend the structural materials and the structure will in turn transfer heat with the fluid and push the fluid. For example, inside a typical engine, the radiation shields in the displacer are very thin and any flexing will change the convection path of the neighboring fluid. Similarly, the flexures will mix the Helium gas changing the effective temperature on the flexure. These, and other interactions are inherently multi-dimensional.

G. Dimensionality of Losses

The primary loss mechanisms may be grouped as mixing, viscosity, and irreversible heat transfer. Mixing is inherently multidimensional. Losses due to viscosity are often found from friction factors determined from experiment. And the losses from heat transfer depend upon heat transfer (film) coefficients that are also experimentally derived. A multidimensional analysis does not require the experimental data.

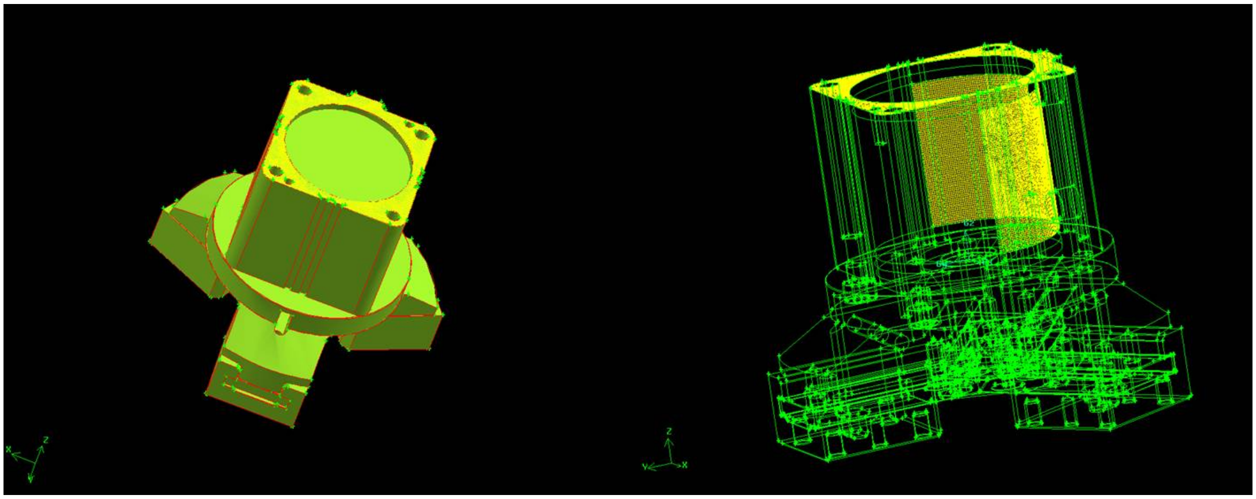


Figure 7. Fitting Parts Together

H. Generating Linear Models for Controls

Computational Fluid Dynamics based linear modeling provides a small perturbation model that can be used for control applications and real-time simulations.[54] By producing a steady-harmonic solution with a multi-dimensional analysis, small changes in the operating conditions of the engine will produce small changes in performance. This information can be used in developing controllers for dynamic response.

VI. Design And Integration Analysis Options

The capability for two-dimensional axisymmetric multidimensional Stirling simulation has recently been demonstrated and the solutions take about a week. However, through a careful integration of multiple solution strategies, a more complete design analysis may be achieved in less time. For example, in Fig. 10, is a road map for achieving a more integrated approach to Stirling engine design.

A. Multi-D Sage

Currently Sage[24] is a one-dimensional Navier-Stokes steady-harmonic solver commonly used in industry for Stirling engine performance analysis and optimization. It's main weakness is its one-dimensional formulation. The solution approach could be extended to two and three-spatial dimensions for very fast solutions of complex engines of all power levels. This would also provide correct boundary conditions for component modeling[55] since current one-dimensional analysis does not provide multidimensional velocity direction.

B. Commercial Transient Code Upgrades

Current commercial codes utilize old techniques that were designed for steady-state calculations. However, the commercial codes are well developed, user friendly, and useful for simulating complicated moving geometry such as occurs in Stirling engines. It is important to utilize this resource for near term results and modest improvements to their regenerator modeling equations would make them useful for design this year.

They can provide improved heat transfer and friction factor correlations for one-dimensional Sage calculations. In addition, gas spring and flexure spring coefficients could be determined multidimensionally for improved System Dynamic Modeling. And finally, an as yet untapped ability is the recently developed

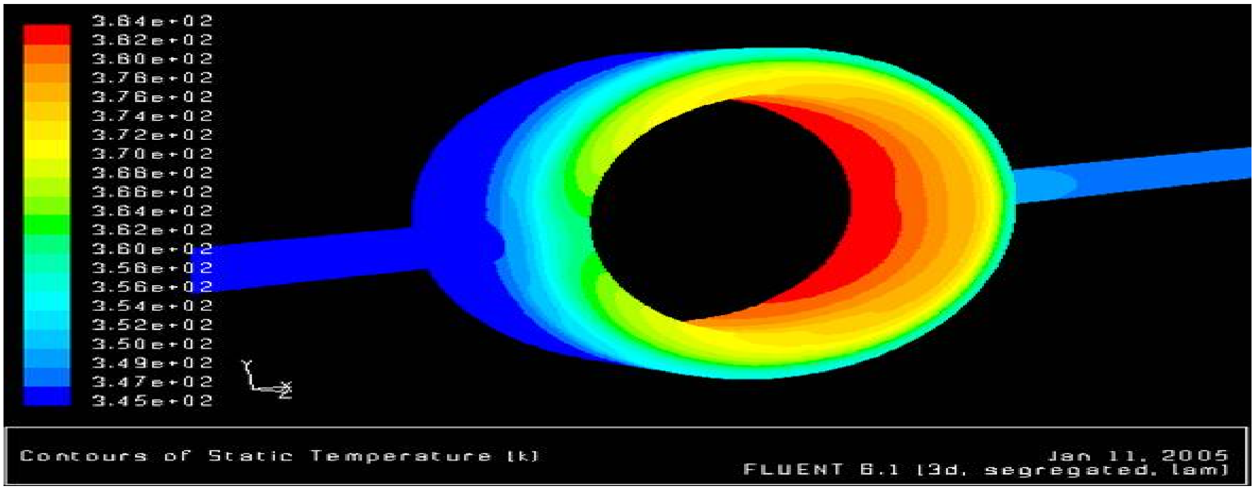
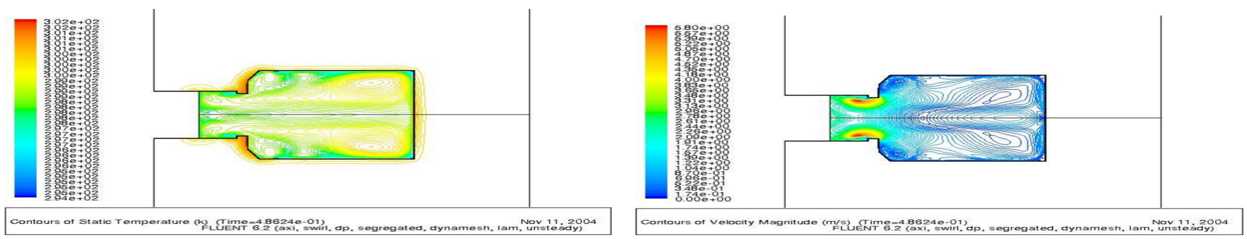


Figure 8. Numerically Derived Correlations



(a) Temperature Distribution

(b) Velocity Distribution

Figure 9. Numerically Derived Temperature and Velocity Distributions

Fluid-Structure interaction capability of the commercial codes. This is still unproven and time-consuming, but offers the possibility of reducing displacer rubbing and improved material selection.

C. High-Order Transient Code Development

A new high-order transient code would be able to efficiently resolve entropy features and turbulence transition. A one-dimensional high order transient code could be incorporated into the SDM to provide thermodynamic as well as one-dimensional system mechanical modeling. And a multidimensional transient code would provide improved correlations for Sage.

D. SDM-CFD Integration

Stirling Dynamic Modeling was mentioned earlier and recent attempts at merging it with Sage have proved successful. However, higher fidelity simulation needs will naturally lead to incorporating multidimensional analysis. An integrated CFD-SDM tool could provide the piston dynamic information for the other analysis tools. By iterating between these tools we would converge to a fully validated understanding of the Stirling design and this is the subject of the next section.

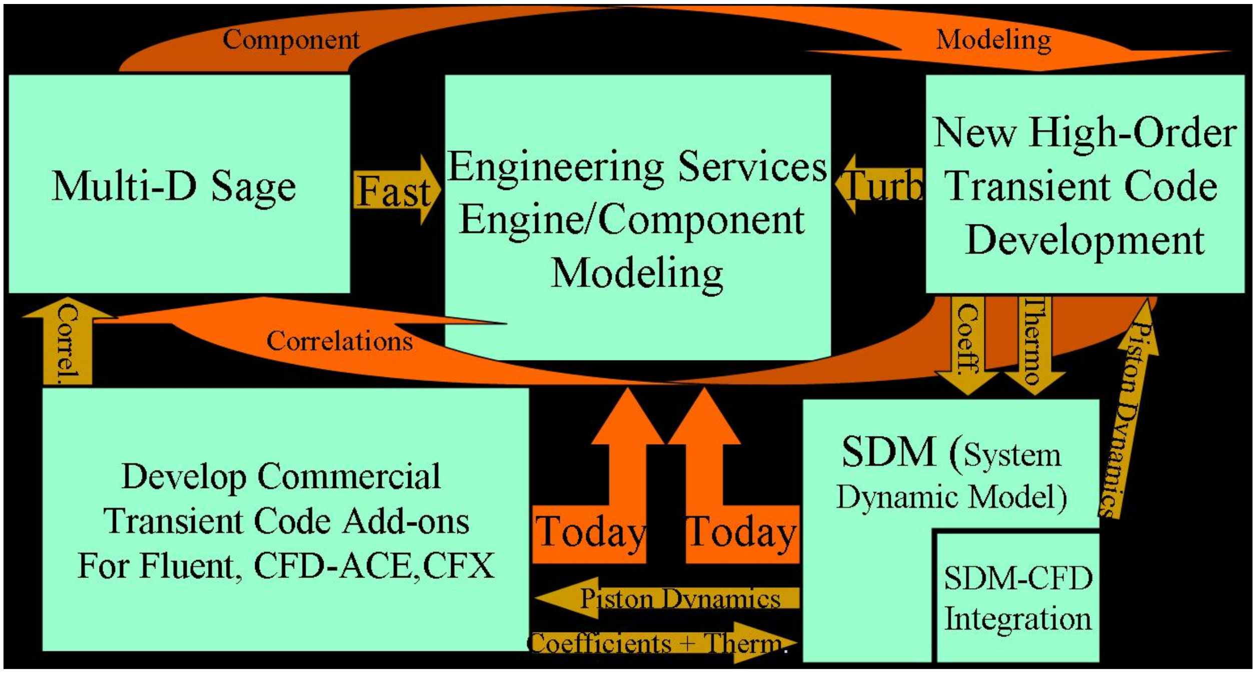


Figure 10. Overall Analysis Design

E. Comprehensive Analysis

The need for multidimensional analysis is great, but one-dimensional analysis is important for quickly providing conceptual designs and optimizations. By combining all these forms of analysis, we could be assured that the first hardware prototype will perform as intended.

As shown in Fig. 11, a logical design path starting with the desired performance and ending with hardware may be followed to generate reliable system solutions. First, after specifying a desired mission power and operating range, a preliminary Sage (or other one-dimensional solver) analysis could be performed. The motion of the piston could then be improved with the SDM analysis. Using those two results, an initial set of CAD drawings of a conceptual engine could be quickly set up and tested in either a two-dimensional axisymmetric or full three-dimensional mode. If the expected results are observed then it can be assumed the empirical coefficients used in Sage and SDM are adequate. Next, optimize the engine in Sage and again repeat the SDM analysis. Repeat the 2D and/or 3D analysis to confirm the results. If at any time the one-dimensional results do not match the multidimensional results then change the emperical coefficients based on the multidimensional results. This process of iterating between one-dimensional and multidimensional results insures the hardware will function as intended.

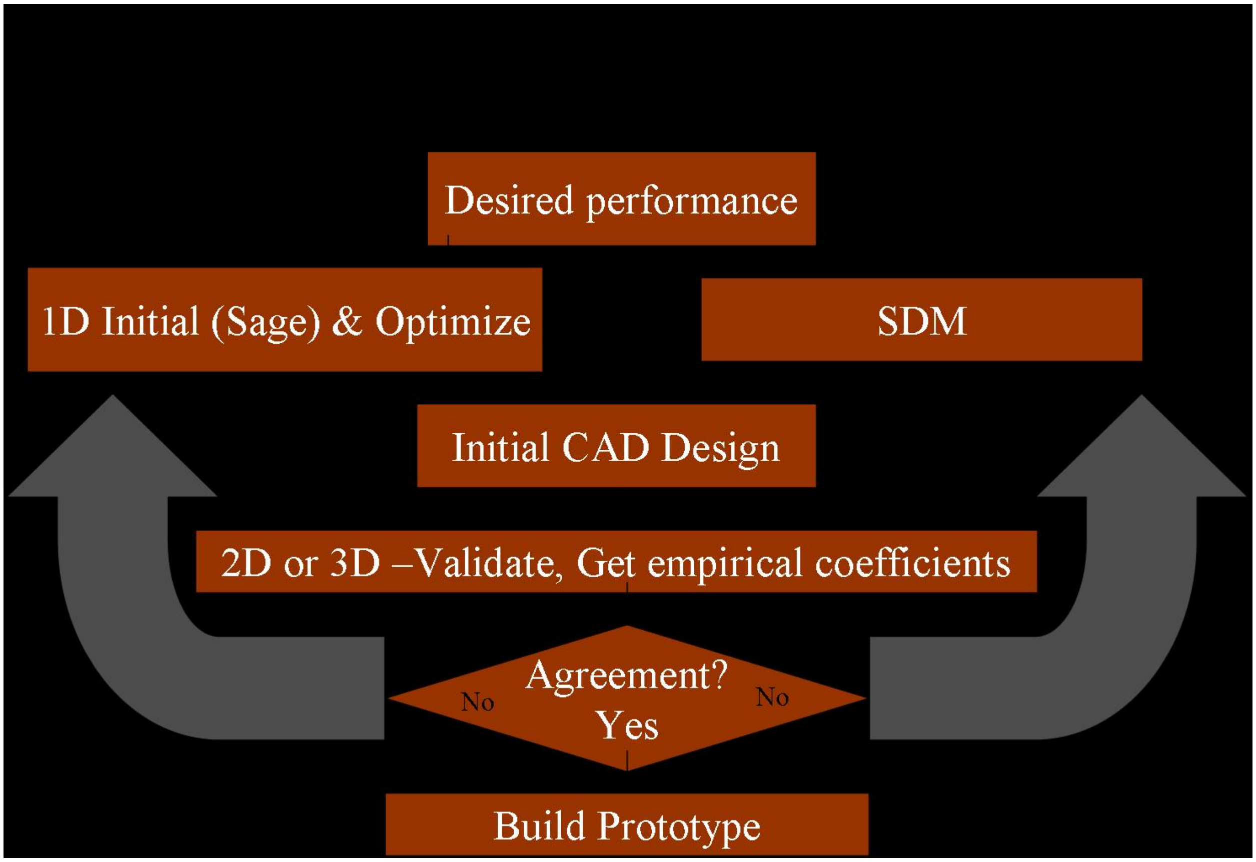


Figure 11. Analysis Integration

VII. Conclusion

These observations lead to the conclusion that one, two, and three-dimensional modeling should all be employed and all three paradigms provide important capabilities that when combined provide a potent combination of initial design, empirical coefficient adjustment, optimization, and final prototype demonstration before the first part is cut.

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Given the cost and complication of simulating Stirling convertors, do we really need multidimensional modeling when one-dimensional capabilities exist? This paper provides a comprehensive description of when and why multidimensional simulation is needed.

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